A High Performance Ku-band Two Channel Downconverter for Interferometric Radar Applications

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Abstract **– This paper addresses the initial stages for the design, construction and testing of a two-channel, two-stage downconverter from Ku-band to IF, where the emphasis on relative phase accuracy and inter-channel cross-talk requirements are critical design elements in the application of the downconverter for interferometric radar applications.**

I. Introduction

Interferometric radar and interferometric synthetic aperture radar (InSAR) are among the evolving technologies in microwave engineering that has grown to meet NASA's needs for earth and planetary exploration in recent years. The development of this technology has resulted in a number of successes, notable among them, a spaceborne mission utilizing NASA's space shuttle to fly a C-band interferometer based on a 60m structure which separated a secondary antenna from the payload-bay antenna.

Because the phase difference between two interferometric channels is the fundamental measurement quantity for these types of observations, the measurement accuracy of this phase difference is of primary importance to the design of interferometric radar. By having a more complete understanding of the characteristics for key hardware components in the interferometer design, a system engineer will be better able to perform the tradeoffs necessary to achieve an efficient and low cost instrument while meeting the necessary performance requirements for the overall system.

A. Interferometric Radar Fundamentals

The basic operation of an interferometer entails the reception of a reflected wave from a common transmitted waveform. For a cross-track interferometer (antennas oriented perpendicular to the direction of platform motion) the phase difference measured by two antennas separated by a baseline, B, and orientation angle, α, can be related to the observing geometry and the topography of the reflecting surface (Fig. 1). In this case, the measured range to target obtained from radar timing is related to the look angle to the target via the measured phase difference, ϕ, between the two antennas of the interferometric pair, $A1$ and $A2$. While the development and discussion of the downconverter in this treatment applies to both cross-track and along-track interferometry, for the purpose of this discussion (and simplicity), the treatment will focus primarily on the cross-track interferometric application.

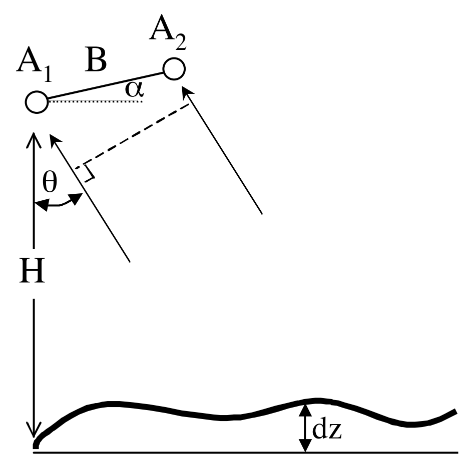

Fig 1. Observing geometry of a cross-track interferometric radar.

For cross-track interferometry, the relationship between the measured phase difference and look angle can be written as

$$\theta = \sin^{-1}\left(\frac{\lambda\phi}{a2\pi B}\right) \tag{1}$$

which is related to the topography through

$$z = H - R\cos\left(\alpha - \sin^{-1}\left(\frac{\lambda\phi}{a2\pi B}\right)\right) \tag{2}$$

The sensitivity of the measured phase to height (in units of rad/m) is given by the interferometric vertical wavenumber, written as

$$k_z = \frac{akB\cos(\theta-\alpha)}{R\sin\theta} \tag{3}$$

where k is the wavenumber ($2\pi/\lambda$), R is the range to the target, and a is a geometric parameter which takes on an integer value of one or two for common transmit (non-ping-pong) and alternating transmit (ping-pong) from either antenna of the interferometric pair, respectively. The expression for interferometric sensitivity to phase is significant in that it highlights the impact of the instrument configuration on the overall sensitivity to the scientific quantity of interest (i.e. height). That is, small changes in the measured phase can be related to small changes in the topographic height by

$$\Delta z(R) = \phi(R)/k_z \, . \tag{4}$$

Note that in addition to the phase difference induced by the signal's angle of arrival to the interferometer, variations in the vertical wavenumber and the differential phase internal to the instrument will also induce topographic-like signatures in the data. For this reason, careful control over the parameters which drive these quantities is an important consideration in instrument design.

B. Importance of Differential Phase Measurement Accuracy

One aspect of the design considerations discussed in the previous section can be found in the choice of the interferometric baseline length. In this case the baseline length is chosen such that the configuration's sensitivity to topography is larger than its sensitivity to variations in the differential phase internal to the instrument. Inspection of (3) and (4) reveals that a given phase error will be proportional the topographic error multiplied by the baseline length. In other words, larger baselines have the effect of deemphasizing phase errors (with the eventual cost of inducing phase wrapping errors). Conversely, by increasing the performance of the differential phase measurement, for a fixed topographic accuracy, the baseline length may be proportionally reduced. For spaceborne and airborne applications this result has important implications for the overall structure and instrument feasibility in terms of cost and realization.

A block diagram for a typical interferometer is shown in Fig. 2. Illustrated here are the two antennas of the interferometric baseline, the signal path from the antennas to RF downconversion chain (labeled DDC) and the downconversion itself. Because differential phase is directly proportional to the measured height and multiplied by the range, as in (3) and (4), control of differential phase directly effects the overall performance of the instrument. As discussed in the previous paragraph too, increase of differential phase measurement accuracy impacts the choice of the baseline length which separates the two antennas of the interferometric pair. Further consideration of the possible sources of error in Fig. 2 shows that reducing the separation between antennas will have the added benefit of reducing the electrical length of the connection between the antennas and the downconversion chain. In other words, increasing the performance of the downconverter has the added benefit of reducing other potential sources of error in the critical signal path of the interferometer.

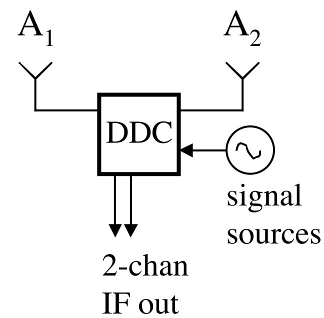

Fig 2. *Block diagram of an interferometric receiver.*

It is for these reasons that this project has chosen to focus on the quality of the differentail signal as it passes through the downconversion chain.

II. KU-BAND DOWNCONVERTER DEVELOPMENT

In addition to the choice of topographic and phase measurement accuracy, the instrument designer must also choose the carrier frequency. The choice of this frequency often involves a number of considerations, including propagation effects, RF component availability, and the signal/target interaction. With all other aspects being equally weighted, a general trend is towards increased frequency (and decreased wavelength). Under these circumstances, for a constant interferometric sensitivity, k_z, described in (3), an increase in carrier frequency allows for a proportional decrease in baseline length, and therefore a decrease in the mechanical structure. Indeed, under some circumstances, the carrier frequency is so low (e.g. L-band), that the only realistically deployable interferometer in space can be through the use of repeat-pass or tandem satellites which suffer from temporal decorrelation and high operational costs. In general then, higher frequencies are preferred for single-pass interferometry, with C-band being an effective minimum, X-, or Ku-band being preferred, and Ka-band a goal.

For this work, a Ku-band system is the current technology under development. This focus benefits from a considerable amount of effort that was put forth on the creation of a spaceborne version of a near-nadir looking interferometer for measuring ocean surface topography, called the Wide Swath Ocean Altimeter (WSOA) that was initially intended for launch in 2008. This instrument, originally part of the Ocean Surface Topography Mission (OSTM) was to fly at an altitude of 1300 km, have a baseline length of 6.4 meters, and measure ocean surface topography to within 7 cm of accuracy. The specifications for the Ku-band downconverter chain, which were adopted for this development, are listed in Table I.

TABLE I
KU-BAND DUAL-DOWNCONVERTER DESIGN CONSTRAINTS

Design Constraint	Ku-band DDC
Signal Bandwidth	20 MHz
Effective Noise Bandwidth	< 30 Mhz
Input Frequency Range	13275 – 13295 MHz
Operating Temperature	-10 to 50 degrees C
Noise Figure	< 4.5 dB
Output Frequency Range	5-25 MHz
Channel to Channel Isolation	> 80 dB
Input/Output VSWR	< 1.5:1
Relative Channel to Channel Phase Stability	0.050 degrees RMS over BW
Receiver Phase Variation over Best Quadratic Fit	3 deg RMS over BW
Receiver Amplitude Variation	2 dB over BW
Receiver Amplitude Variation over Best Linear Fit	0.3 dB RMS over BW
Input Signal Range	-100 to –65 dBm
DDC End to End Gain	65 to 70 dB
Image Rejection	> 30 dB

To achieve the development goals listed in Table I, especially the relative channel to channel phase stability (highlighted), requires two critical components of effort. These are: i.) creation of a downconverter design that is expected to meet these requirements and ii.) development of measurement methods that can measure the performance of the downconverter to the required degree of accuracy. With respect to this last component of the development effort, by developing measurement tools and methods that are capable of achieving a high degree of accuracy is critical in not just verifying the overall downconverter performance, these tools may also be used for determining those components of the downconverter system which dominate the performance, and therefore provide focus for further improving that performance.

A. Device Development

The development of the Ku-band downconverter is taking two stages. The first is the creation of a simple connectorized breadboard system for creating a baseline for system performance and to serve as device for refining the test measurement system. A simplified block diagram for the downconverter is shown in Fig. 3, which shows the two channels of the downconverter, as well as various amplification and filtering stages. For the downconverter being designed, the reduction of frequency from Ku-band to the video frequency (5-25 MHz) takes place in two stages: one from Ku-band to L-band, and then from L-band to baseband. The L-band intermediate frequency is used for performing image reject filtering and signal amplification. Not shown in this figure is the common source LOs at Ku-band and L-band, potential sources for inter-channel cross talk.

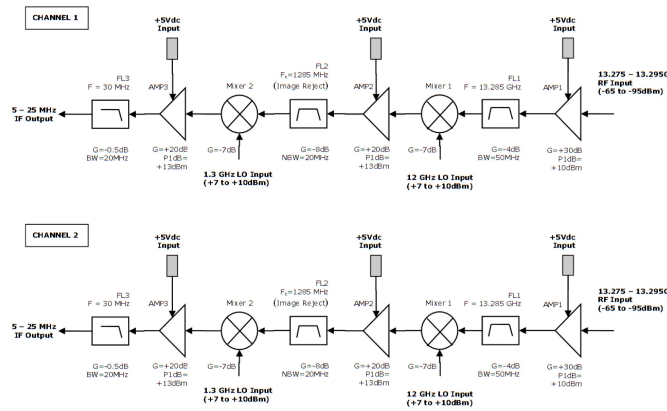

Fig 3. *Block diagram of the two-stage, two-channel Ku-band downconverter.*

The second stage of Ku-band downconverter development will be implemented on Parts Wiring Boards (PWB) incorporated into a machined chassis using low-cost surface mount components on Rogers 6002. This laminate material was chosen for its low thermal coefficient of expansion and low thermal coefficient of dielectric constant. Separate RF tight cavities are used to minimize the inter-channel crosstalk and to suppress the excitation of cavity modes. The integrated chassis and PWB design has also taken into account the need for mechanical and thermal symmetry between the two downconversion channels in order to minimize imbalances that may occur in the differential phase performance under conditions of moderate thermal stress. For this reason, the entire chassis will be constructed out of a single-block of aluminum, machined to house the various PWB assemblies. Further monitoring of temperature fluctuation and control of DC power to the active components will also be implemented. A photograph of the current breadboard assembly and the planned mechanical layout is shown in Fig. 4 on the following page.

B. Measurement Methods Development

Based on experience and an initial assessment of available resources, it has become clear that one of the greatest challenges in creating a test setup for the Ku-band downconverter will be achieving the high degree of phase measurement accuracy required to characterize (and optimize) the system. It was further expected that this aspect of the development would be particularly problematic due to the frequency conversion stages which are fundamental to the downconversion process.

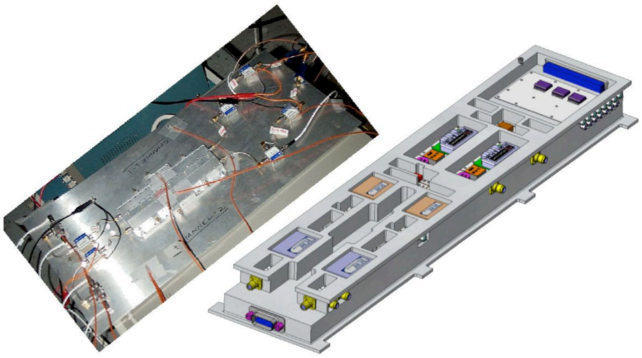

Fig 4. *Photograph of the current breadboard design and a CAD drawing of the planned mechanical layout.*

For these reasons, considerable effort has been put forth into formulating a methodology for performing measurements of phase and amplitude over the system bandwidth of 20 MHz (see Siqueira et al., 2006). The basic component of this methodology is to provide analytic expressions which relate the test measurement accuracy of amplitude, phase, frequency and chirp rate to the measurement system variables of signal to noise ratio (SNR) and the number of samples in a measurement. Hence, rather than relying on the presence of multistage precision network analyzers, the test measurement system used for characterizing the two-channel downconverter consists of a signal source (sinusoid and/or function generator) and a high-performance AtoD converter (e.g. a digital oscilloscope). This system has been assembled and tested in the lab, and is shown in Fig. 5 below.

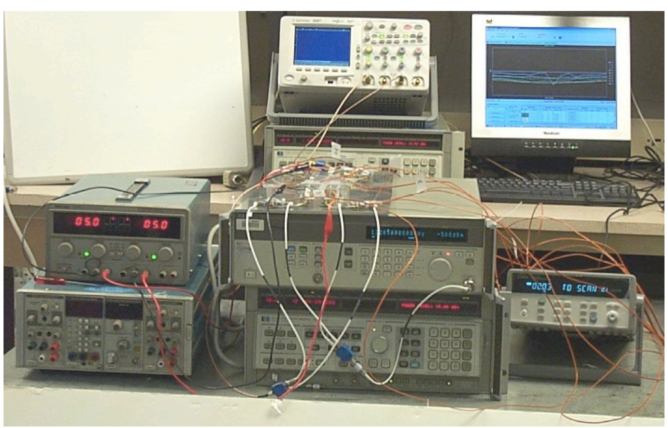

Fig 5. *Photograph of the Ku-band test measurement system.*

In this system, test components are controlled by a central PC running Matlab data acquisition software. The PC computer both controls the test measurement equipment and collects data; from a data logger for measuring temperature profiles and from the LAN port of the digital oscilloscope, capable of digitizing waveforms up to 4 million samples on two channels with a 4 GHz sampling rate (Fig 6). All sampling in this system takes place of the baseband signal from 5 to 25 MHz.

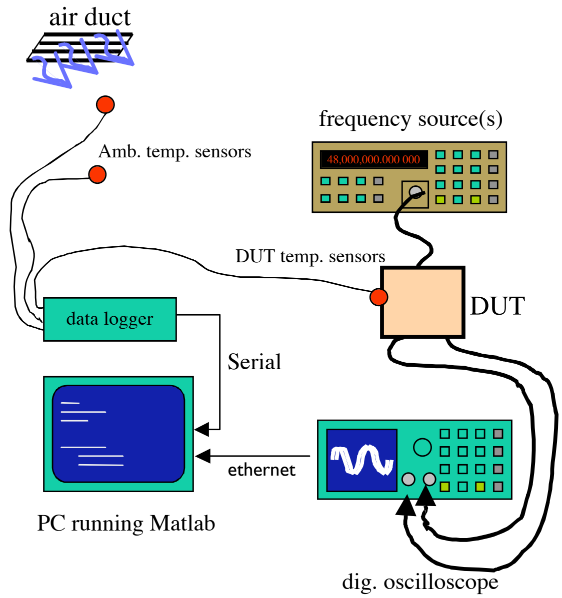

Fig 6. *Schematic diagram of the test setup.*

In the above setup, special attention has been paid to measuring temperature, and temperature gradients, because it is expected that small temperature fluctuations will induce slight changes in the electrical length and behavior of components at the Ku-band RF frequency, and therefore will be the principal source of differential phase error for the downconverter design.

Prior to measuring downconverter performance however, it is desirable to verify the performance of the test measurement setup. This is accomplished by feeding a common signal at baseband (e.g. a 15 MHz sinusoid) from the signal into a splitter and then directly into the two channels of the digital oscilloscope. Under this configuration, theoretical performance expectations can be compared with direct measurements and the test setup verified to the degree that the setup is the dominant source of error.

An example of the test setups measurement performance is illustrated in Fig 7, where a 15 MHz sinusoid is sampled at 4 GHz for 100 μsec to collect 400,000 points every 30-50 seconds. Assuming a 30 dB SNR, the theoretical limit to estimate performance is 2.9 millidegrees. Measurement of the phase difference under the test setup shows a measurement error of 3.9 millidgrees; hence the null hypothesis that there is no phase difference between the two channels is accepted under the accuracy of this measurement configuration.

Note too, in Fig 7, there is no clear trend in the differential phase estimates. This is a further indicator that whatever errors are in the measurement system, they are either i.) below the measurement capacity of the setup, or ii.) not systematic as a function of time (i.e. they are random).

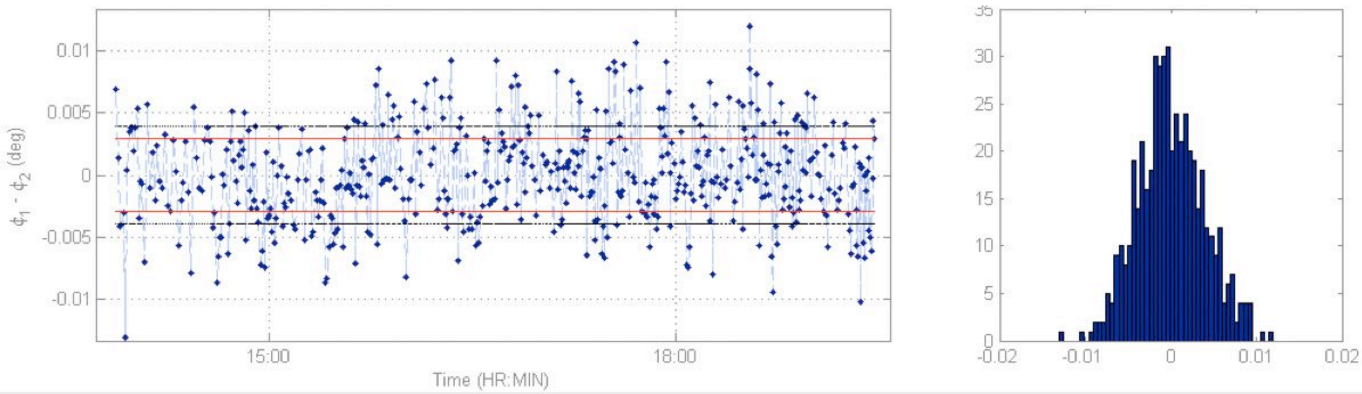

Fig 7. *Illustration of test setup measurement performance. Two channel phase difference is estimated as a function of time using a 15 MHz sinusoid. The plot to the left shows the calculated phase difference (symbols), standard deviation of the phase difference (horizontal black line) at +/- 3.9 mdeg,, and the theoretical standard deviation (Cramer-Rao lower bound) using 400,000 points and assuming a 30 dB SNR. The histogram to the right shows the overall distribution of the phase differences.*

With the test measurement system demonstrated to have sufficient accuracy to measure phase differences on the order of four millidegrees, an order of magnitude below the phase performance of the downconverter, it is now possible to insert the downconversion chain into the system and measure its overall performance. This was done using the breadboard downconverter shown in Fig 4, which is composed essentially of connectorized components mounted onto a single sheet of aluminum, resting on top of the signal generators shown in Fig 5.

The phase difference measurement results are shown in the upper plot of Fig 8, where a periodic signature of phase differences on the order of +/- 0.4 degrees every 20 minutes can clearly be seen. This periodic and downward trend in the phase difference data has been directly related to the measured +/- 1 degree Centigrade shifts of temperature of the downconverter assembly, and is associated with a cyclical heating schedule in the laboratory environment. By making the assumption that all slowly varying trends in phase difference data are due to the thermal cycles within the laboratory and the thermal inertia of the downconverter, it is possible to fit a low frequency curve to the data and remove it to analyze the residual phase differences. This was done to create the lower plot of Fig 8, where it can be seen that the cyclical and downward trends have been removed. The standard deviation of this residual about the mean phase difference is calculated to be 40 millidegrees, well within the downconverter's measurement goal of 50 millidegrees specified in Table I.

Once it became clear that i.) the test measurement system would be accurate enough to characterize the downconverter to the desired accuracy and ii.) that the downconverter indeed was primarily sensitive to temperature fluctuations, the entire breadboard system was moved to a thermally isolated environment (known in layman's terms as a "cooler"). This setup is shown in Fig. 9.

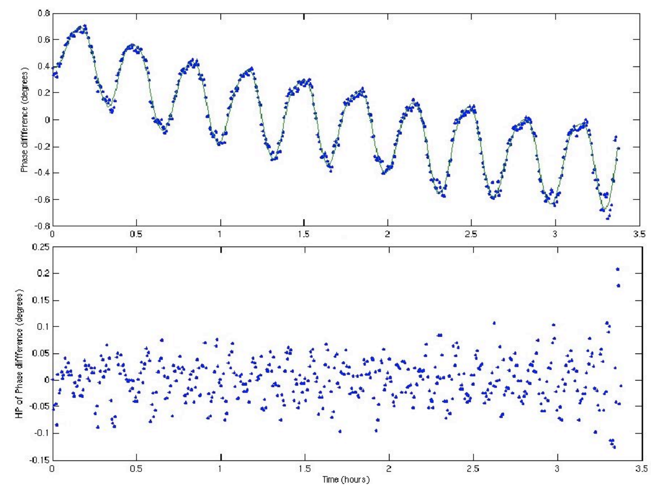

Fig 8. *Phase difference measurements for a common signal injected into two channels of the downconverter. The top plot shows the phase differences (symbols) and a low frequency curve fit to the differences. The lower plot illustrates the residual phase differences after removing the slowly varying trend.*

Under the thermally isolated environment, two sets of measurements were made. One, with the environment closed, yet allowed to operate under its own ambient temperature (approximately 23 degrees C), and the other, where ice was introduced to an open chamber below the two-channel downconverter system, thus creating an ambient temperature of approximately 17 degrees C. Measurements of phase difference in the former case showed a phase accuracy of approximately 40 millidgrees (in agreement with the results from Fig 8), where for the latter case (cooled), the phase difference error was on the order of 20 millidgrees (Fig 10), a factor of two improvement. Given the discussion relating phase measurement accuracy to baseline length, and the fact that these measurements are for a simple breadboard version of the full downconverter, there seems to be room for significant optimism in the overall development effort's progress.

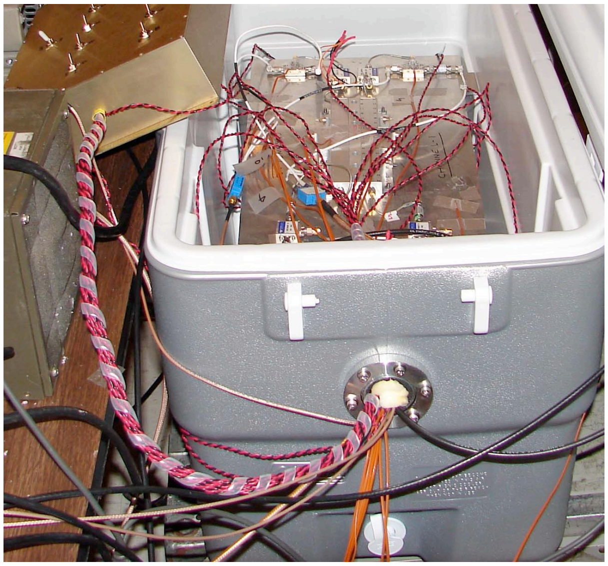

Fig 9. *Photograph of the thermally isolated test setup. Shown in the upper left is a control box to create temperature gradients across the downconverter.*

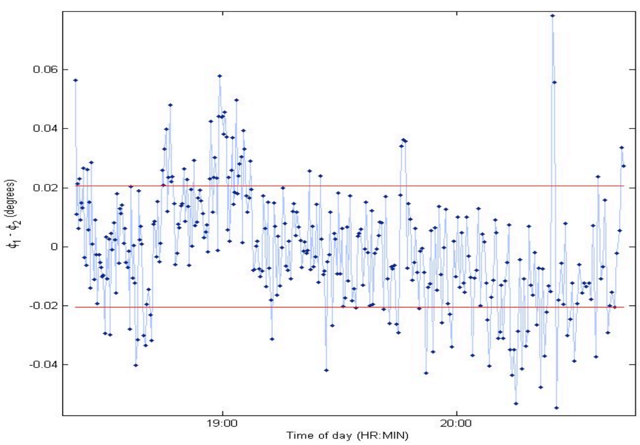

Fig 10. *Measured phase differences in the thermally isolated environment. In this experiment, ice was used to keep the device temperature to 17 degrees C (23 degrees C was typical for room temperature measurements).*

III. CONCLUSION

In this paper, the motivation behind creating a high performance two-stage, two channel downconversion system was discussed in the context of cross-track interferometry. Given that motivation, and a table of design goals (Table I), the design philosophy for a PWB version of the downconverter into solid block of aluminum was given. An early implementation of that final downconverter has been implemented into a breadboard model, which has been characterized in a laboratory environment to determine the differential phase performance of the downconversion chain. To achieve the accuracies required by the downconverter, it was necessary to implement a custom test environment whereby signal to noise ratio and the number of samples could be adjusted to achieve the desired measurement accuracies. The performance of the test setup was shown to meet measurement accuracies of better than 4 millidegrees, an order of magnitude smaller than the downconverter's performance requirements. This test setup was then utilized to characterize the downconverter when it was exposed to the open laboratory environment and under a more thermally isolated environment. Under the thermally isolated environment, it was shown that the two-stage downconverter could achieve differential phase accuracies to better than 20 millidegrees, at 17 degrees C, a fair margin below the overall devices' accuracy goal of 50 millidgrees. As a result, it appears that the fully developed downconverter is likely to meet the goals set out in Table 1, with remaining efforts on this specific aspect of the development expected to concentrate on the potential for inter-channel cross talk, and maintaining the performance parameters over a wider temperature range and the 20 MHz bandwidth.

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